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Significant discrepancies between stellar evolution models and solar-type eclipsing and visual binaries ?

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Abstract. Individual components of well-detached binary systems are assumed to be two single-like stars with a common origin, i.e. they share the same chemical composition and same age. Therefore, one expects to fit the observed parameters of both components with a single isochrone at the same metallicity. We show that serious problems appear for systems with accurate fundamental data (eclipsing binaries in the field and in the Hyades, and a visual binary) in the 0.7-1.1 $M_\odot$ mass range. We discuss and briefly review the results obtained so far on these objects. Finally, in an attempt to solve this problem, we present new projects, both on the theoretical and the observational sides.

1. Introduction to the problem

The study of stars with masses larger than ∼0.6 $M_\odot$ bypasses difficulties in the treatment of the equation of state and the atmosphere. On the other hand, stars with masses greater than about 1.1 $M_\odot$ have a permanent convective core, introducing an additional parameter, the amount of overshooting. Therefore, we expect current stellar evolution models to be able to match the basic properties of stars in the 0.7-1.1 $M_\odot$ mass range. In particular, some detached binaries provide very accurate stellar data so they are ideal candidates to critically test sets of theoretical models. Nevertheless, as pointed out by Popper (1997), *a serious dilemma appears to be present in the comparison of fundamental stellar properties derived from observations and the predictions of stellar models.* In the next sections we review stellar objects (EBs in the field and in the Hyades and one visual binary) suggesting that current stellar models present some problems around the mass of the Sun.

2. Eclipsing binaries in the field

We consider the following detached eclipsing binaries (DEBs): RT And, HS Aur, CG Cyg and FL Lyr. We obtain bad fits by fitting both components simultaneously in the HR diagram with Padova group (Fagotto et al. 1994) or Geneva group (Mowlavi et al. 1998) models. Either these stellar models are unreliable in this part of the HRD, or the T_{eff}s of (at least) the secondaries need revision. As shown by Pols et al. (1997), the same difficulty appears with the Cambridge group models by fitting simultaneously the effective temperature (T_{eff}), mass (M) and radius (R). Clausen et al. (1999) recently reviewed this dilemma with other sets of theoretical models, getting bad fits as well.
Could the measurements be responsible of this problem ? The relative error on the individual T_{eff}s of the sample is always small (<3.5%). However, while the mass and radius of each component of DEBs can be accurately measured (1-2%), the use of T_{eff} (and so luminosity) is not as reliable because derived indirectly (from various photometric or spectroscopic indicators) and thus may explain part of the problem. Lastennet et al. (1999a), Ribas et al. (2000), and Lastennet, Cuisinier & Lejeune (these proceedings) attempted to carefully re-derive reliable EBs T_{eff}s, but unfortunately none of these works study the stars in question because individual *uvby* photometry would be necessary. Mass transfer should not be an explanation because none of these stars overflows its Roche lobe (Lastennet 1998): HS Aur A: ∼11%, B: ∼10%; FL Lyr A: ∼35%, B: ∼29%; CG Cyg A: ∼61%, B: ∼60%; RT And A: ∼77%, B: ∼64%. Nevertheless, for the system RT And, the face-to-face position of the spots on the surface of both components may indicate the possibility of a mass transfer from the primary to the secondary component through a magnetic bridge connecting both active regions (Pribulla et al. 2000).

3. Eclipsing binaries in open clusters

As discussed for instance by Lastennet et al. (2000), DEBs members of a star cluster provide stringent constraints on stellar evolution models when the metallicity of the cluster is known. The eclipsing binary V818 Tauri (a member of the Hyades) contains 2 stars in the 0.7-1.1 $M_\odot$ mass range (1.072+0.769 $M_\odot$, Peterson & Solensky 1988). Once again, a similar analysis for this binary (Lastennet et al. 1999b) found no Padova models fitting simultaneously M and R (thus, without using any information on T_{eff}) for any age or metallicity.

4. Visual binaries

Such a problem was also detected in this mass range by Fernandes et al. (1998) for 85 Peg (0.91±0.11 $M_\odot$+0.73±0.13 $M_\odot$), a nearby visual binary star (∼12.4 pc). They found no solution satisfying the constraint of the luminosity (L) and T_{eff} for both stars and corresponding to the observed metallicity and sum of the masses. 85 Peg A and B appeared to be too cold and/or over-luminous with respect to the ZAMS. Only models with extremely low helium (Y<0.20) and high age (20 Gyr) could fit the HR diagram position of 85 Peg A, which seems definitively unrealistic since the primordial helium is estimated to be

Y=0.232±0.003 (Olive & Steigman 1995) and the age of the Universe to be between 10-20 Gyr. They succeeded to fit the 85 Peg A position by decreasing α_{MLT} to about 1.0 but a similar change of α_{MLT} didn't fit the 85 Peg B position. A more recent study (Lebreton et al. 1999) shows that including the diffusion, the contribution of the α-elements, and non LTE-effects in low metallicity models help solving the above discrepancy, but there is still a problem to match the mass of the secondary. A new study of 85 Peg is underway (Fernandes et al., in prep.) but the influence of rotation can already be excluded because vsin$i$ is very low (vsin$i$<5 km.s^{-1}, according to the catalog of Glebocki & Stawikowski, 2000).

5. Future theoretical projects with CESAM

The systematic discrepancy presented previously is not observed in CD Tau C, a solar mass companion of the triple system CD Tau: Ribas et al. (1999) obtained a perfect fit of the 3 components with a single isochrone. Therefore, except CD Tau C (whose mass still needs an accurate measure), the other examples show that there is still great problems for the stellar evolution theory to predict the properties of solar-type stars. However, this is of first importance for stellar theory to match at least the best known objects (the Sun and non-interacting binary systems) before any attempt to derive information for star clusters or stellar populations in galaxies. To tackle this problem, the CESAM code (Morel 1997) should be very useful to explore the influence of each physical parameter. CESAM performs calculations of 1D quasi-static stellar evolution including diffusion and mass-loss and computes the evolution of stars from the pre-main sequence (PMS) to the beginning of the red giant branch.

As suggested by Clausen et al. (1999), the problem briefly presented in the previous sections may be removed (or at least diminished) if a significantly lower α_{MLT} is adopted for the less massive secondary components. A recent study on V818 Tau (Lebreton et al. 2001) seem to support this idea and similar tests on the EBs of §2 are in progress (Lastennet & Fernandes). We suggest a detailed study of each system to check if there is a solution for a set of (α_{MLT}, Y, Z, age). Even if the effect of stellar rotation is usually negligible for stars less massive than ~1.4 $M_{\odot}$, an even slightly effect on $T_{\rm eff}$ and L may be relevant for some of these stars (e.g. vsin$i$ ~70 km.s^{-1} for both components of CG Cyg). Another explanation may be that some of these stars are still in the PMS phase, and this is another advantage to use the CESAM code which includes this phase.

6. Future constraints from new observational campaigns and GAIA

Of course, the number of relevant systems is still very small to give a definitive conclusion. A photometric and spectroscopic observational campaign of about 50 newly discovered Hipparcos EBs at OHP (France), Kryonerion (Greece) and Cracow (Poland) would increase the number of objects (Kurpinska-Winiarska & Oblak 2000), as well as the dedicated observational program of late F, G and K type stars at the Danish 50 cm SAT (La Silla Obs., Chile) which already provided new candidates (Clausen, Helt & Olsen 1999). The GAIA satellite would also increase the number of stars with individual masses. Halbwachs & Arenou (1999) estimated that the individual masses of 79 double-lined spectroscopic binaries

(SB2s) - which are not eclipsing binaries - in the 8^{th} catalogue of orbital elements of SB systems (Batten et al. 1989) would be derived from the GAIA astrometric observations. We expect some of them ($\sim$ 10 according to Tab. 1 of Halbwachs & Arenou) to belong to the mass range discussed in the present work.

7. Conclusion

We review solar-type stars showing a clear discrepancy between their fundamental properties and stellar model predictions. This indicates problems in current stellar evolutionary models because a revision of their $T_{\rm eff}$ would not solve the disagreement regarding the masses and radii (see Tab. 7 of Popper 1997, or Fig. 4 in Lastennet et al. 1999b). These stars belong to binary systems without interaction so representative of single stars, and it is of first importance for stellar theory to match at least the best known objects (the Sun and non-interacting binary systems). In an attempt to solve this problem, we suggest some theoretical explorations, in particular a detailed study of stellar rotation and PMS phases. We also present some projects which should help to increase the limited number of accurate fundamental parameters of detached EBs.

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